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BACK PACK PORTABLE THERMOELECTRIC GENERATOR

FINAL REPORT

U.S. NAVY - BUSHIPS

CONTRACT NO. NObs - 78197

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NEW PRODUCTS LABORATORIES
Westinghouse Electric Corporation
Pittsburgh 35, PA.

FINAL REPORT

BACK PACK PORTABLE
THERMOELECTRIC GENERATOR

U.S. NAVY - BUSHIPS
Contract No. NObs-78197
(W)G.O. No. WG 78890-CE

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INTRODUCTION

This final report describes in detail the engineering and analytical work performed in the development of a light-weight, portable thermoelectric generator under Navy Contract NObs 78197. The fabricated generator was delivered to the Naval Engineering & Experiment Station at Annapolis, Maryland and is presently undergoing further evaluation and environmental tests at this facility.

The design of the generator was basically guided by the contract specifications. However, as the contract was of a development nature, interpretation of the aims and other guidance were provided by Code 450 of Buships. Listed below is a summary of the most important provisions of the contract. The order is used to indicate the relative importance of these aims.

1. 500 watt output or highest obtainable power output in 35 pounds.
2. Size - within volume limitations of standard Marine Corps back-pack.
3. Nominal load voltage of 24-28 volts.
4. Fuel - leaded gasoline.
5. Modular design for replacement or by-passing of failed thermoelements.
6. Operation in standard military environment.

Preliminary design calculations and laboratory experiments with the thermocouples available at the time the work was initiated indicated that a conventional hermetically sealed generator with forced convection cooling would have a net power output of approximately 280 watts for a 35 pound unit. The low specific power (output power/unit weight) in this type of design is in large part due to the weight of the spring braid assembly and the large temperature drops occurring across the braids and across the electrical insulation between the cold straps and heat exchanger plate. (Refer to Figure 1). These drops become larger as thermocouple element length is decreased (and thermal flux density increased), in an attempt to obtain higher specific powers. Even with a flux density as low as 30 watts per square inch, these temperature drops are approximately 70°C or 20% of the total temperature difference available with a 450°C hot side. Figure 2 indicates this relationship for a specific design of this type having a given heat exchanger and forced convective cooling system. Thus, it is apparent that the cold side configuration in this design introduces a substantial reduction in both specific power and efficiency.

Since this conventional design would give a power output only half as large as desired for the specified weight, a radical design departure was proposed which was known to have severe technical problems but which, if successful, would produce a generator having more than the desired power capability for the specified weight.

This final report on the project will describe this design in detail, will summarize the various phases of the engineering work performed, and will show by thermal and electrical performance data the extent to which this first unit met its design goals.

Important Design Features

One of the basic features of the proposed design was the direct connection of the heat exchangers to the thermoelectric elements. This reduced the cold side temperature drops to a negligible amount but required that the modules be unsealed so that cooling air could pass directly over the heat exchangers as shown in Figure 3.

This design feature immediately raises the question of the effect of air on couple life and the limitation such an operating environment places on the permissable hot side temperature. Although neither of these effects has been evaluated extensively or completely to date, preliminary tests indicated that acceptable life might be obtained with the then existing technology at 450 to 500°C in air. Consequently, couples of sufficient performance and life were available to fabricate a unit which could demonstrate the basic operation of such a generator design and point the way to designs of even higher specific powers.

A second basic design feature is the use of forced convective cooling. This type of cooling is necessary in order to handle the high heat fluxes that a unit of this type must utilize if weight is to be kept to a minimum. A possible design using free convective cooling with a secondary heat transfer fluid was considered early in the development program but this introduced two problems: spring-braids were necessary to conduct the heat to the boiler, i.e. the chamber containing the fluid; and the free convective heat exchanger, tubing, boiler, and heat transfer fluid introduced undesireably large volume and weight penalties. The geometrical freedom that such a design permits is, however, a real advantage and further design work in this area might yield a satisfactory solution.

Forced convective cooling does introduce a noise problem in a generator application of this type. Care must be taken that no resonances are encountered. The rate of air flow is also important as far as the noise amplitude is concerned. Although the final design of this generator utilized a rather high air flow, this was done not because it was necessary in the optimization of the specific power as will be shown later, but because insufficient information was available at the time on the performance of the thermoelectric cold side joint at

higher temperatures. Since this question has since been resolved, future designs would operate at a considerably lower flow with less blower noise.

Another basic feature of the design is the high packing factor or small spacing between thermocouples which is used. This was done so that the lowest contact resistance (between the thermoelectric pellets and the straps) could be obtained for a given thermal flux. Ordinarily such tight spacing introduces a problem in obtaining flexible electrical conductors between adjacent couples. To circumvent this problem, a special heat exchanger was developed which provided not only an electrical path for current but also the necessary flexibility and mechanical pressure loading to obtain good thermal contact of the hot straps to the core.

Another important design feature is the interchangeability of gasoline and propane burners with this design. Although certain problems remain to be solved with the gasoline burner, several laboratory units were built and operated in the same geometrical configuration as used for the propane design. They performed satisfactorily as far as efficiency and heat flux were concerned but were handicapped by noise and other problems, which are discussed later in the report.

Modular design of the thermoelectric ladders was also used so that rapid replacement of a damaged or failed unit could be made if necessary. Eighteen modules consisting of right and left hand types were used so that only two types of spares would be required. The generator design is such that no special tools should be needed to make such replacement.

Design Parameters

The design calculations of couple performance and other couple limitations essentially set the bounds of performance required for the various components if the specification were to be met. The choice of a hot side temperature of 450°C was made on the basis of preliminary life tests; even steady-state operation for moderately long periods in air at 500°C did not cause a severe decrease in couple performance. Such a temperature would be encountered under no load generator operation because of the decrease in Peltier cooling.

The choice of a specified cold side operating temperature was investigated for the particular case in which both couple and heat exchanger geometry were held constant. In this case, the choice of cold side operating temperature was rather insensitive in its effect on system weight over rather a wide range. (Refer to Figure 4) This is due to the fact that both blower weight and blower requirements are reduced as moderately high cold side temperatures are chosen.

As higher cold side temperatures are reached, however the power output per couple starts to decrease more rapidly and a significantly larger number of couples with a corresponding increase in structure are needed to maintain the power output.

Another factor which influenced the choice of the cold side temperature was lack of available information on the life of the joint between the couple and heat exchanger at elevated temperature. As a consequence, a temperature of 120°C was chosen as being quite safe and one which would allow a choice of many soft solder alloys as a joint material. There were, however, two disadvantages in choosing a temperature this low: first, operation at this temperature would require a rather high air flow with resultant acoustical noise; and second, the pellets would have a higher thermal gradient across them and consequently higher internal stress levels than had been present in previous designs.

During the initial phases of this contract, very little information was available which would relate the performance of the burner systems and the parameters of generator design. Initially core or hot side temperature and thermal flux level were taken as the parameters relating the generator to the burner. Subsequent calorimetric testing indicated that for the burner designs investigated, the internal screen or baffle design was more critical in its effect on efficiency than were the core temperature and flux over the range of 300 to 500°C and 30 to 75 watts/in^2 thermal flux.

Couple Design and Performance

As indicated earlier in the report, certain basic restriction were placed upon the geometry of the thermoelectric couple to make it compatible with the over-all design philosophy and other component parts of the system. Rectangular geometry was dictated by the desire for a high packing factor; a nominal 1/4" height was chosen to keep thermally induced stresses at reasonable levels and yet obtain a sufficiently high power density; and geometrical symmetry was desireable so that the heat exchanger-electrical connectors compatible with the thermoelectric couples would present a symmetrical shape to the flow of cooling air.

Three Basic Designs

With these considerations in mind, three basic couples were constructed for comparative testing of electrical performance. In each case, the N and P legs were congruent. These legs were joined to a 1/16" thick iron strap and were spaced 1/16" apart. Thus when these couples are spaced 1/16" from each adjacent couple, a high packing factor is obtained along with geometrical symmetry.

The three pellet geometries tested were: 1/4"W. x 1"L. x 1/4"H.; 1/2"W. x 1/2"L. x 1/4"H.; 1/4"W. x 1/2"L. x 1/4"H. These are all nominal dimensions.

The electrical performance of couples made of these three geometries operating between 120°C and 450°C were obtained and averaged values are listed in Table I.

	TYPE I	TYPE II	TYPE III
Pellet size (WxLxH)	1/4"x1"x1/4"	1/2"x1/2"x1/4"	1/4"x1/2"x1/4"
Measured EMF	121 mv	121 mv	121 mv
Measured resistance	2.0 mΩ	1.72 mΩ	2.98 mΩ
Measured power	1.83 watts	2.33 watts	1.30 watts
Calculated power	2.6 watts	2.6 watts	1.3 watts
Power/Volume	14.6 watts/in^3	17.8 watts/in^3	20.8 watt/in^3
A/ℓ (metal strap)*	0.20"	0.06"	0.10"
A/ℓ (pellet)	1.0"	1.0"	0.5"

*Computed by defining ℓ as the distance between the centerlines of the P and N legs.

TABLE I

COMPARISON OF VARIOUS COUPLES EVALUATED

On the basis of comparing the $\frac{A}{\ell}$ of pellets, it would be assumed that Type I and Type II couples would produce twice as much power as a Type III couple. The superiority of Type III couples in this comparison is probably explained by the fact that it has a better $\frac{A}{\ell}$ for the metal strap than Type II couples and that there is less difficulty of obtaining a metallurgical bond over the complete pellet surface and less cracking than in the 1" long pellets of Type I couples.

These results give the Type III couples two advantages over the others: a higher specific power and a close agreement with calculated performance. Therefore, thermoelectric couples with Type III geometry were chosen for the generator. (Refer to Figure 5)

One further comment on geometry is appropriate here. Ioffe has developed a formula for attaining maximum efficiency from a geometry of equal leg lengths that involves cross-section areas and corresponding thermal conductivities and electrical resistivities. Using Ioffe's formula with the effective properties of these materials gives a calculated efficiency of 6.52 percent, with equal areas an efficiency of 6.5 percent. Thus, only 0.02 percent efficiency would be lost by picking cross-sectional areas equal rather than choosing them to comply with Ioffe's maximum efficiency formula. This difference is insignificant in this application. Furthermore, the accuracies with which the materials properties are measured and the quality control of the material and couple fabrication do not give data which is more accurate than ±5 percent.

Performance

A comparison between the calculated performance of the thermocouple used and the actual performance of experimentally measured samples operating between 450°C and 120°C is as follows: calculated performance - 1.3 watts/couple; developmental samples - 1.3 to 1.2 watts/couple; early production samples - 1.1 to 0.80 watts/couple; final production samples 0.9 - 0.7 watts/couple; and the average initial performance in the generator - 0.8 to 0.7 watts/couple. This, of course, indicates that severe problems arose in processing and fabrication consistency during the production run for the generator. Certain modifications and improvements have been made since then, which have improved couple performance considerably, giving initial power outputs of 1.5 - 1.4 watts/couple. Processing is also under more exact control and it appears that production quantities may now be made without undue reduction in performance.

Another problem which arose is the undesirably rapid degradation of performance of thermocouples running in air upon thermal cycling. Testing in air without cycling had indicated that with the available technology, 1000 hours could be obtained with 10 to 15 percent degradation at either 450 or 500°C hot side temperature. However, the effects of thermal cycling were more extreme, causing an additional 25 to 30 percent degradation in 1000 hours if applied in 2 hour intervals. Since the delivery of the demonstration generator, work has continued toward solving the degradation problem. The exact mechanisms of failure are being examined in detail; many proposed contact and hardware changes are being evaluated. Several of these look promising, but it is still too early to ascertain the exact magnitude of the improvements as applied to the specific geometry and temperature gradient in this couple. In addition, further encapsulation work is being done which, if successful, will substantially improve couple life also. A major portion of this development work is being performed under the Module Improvement Program (NObs-84329).

Mechanical Strength of Couples

While electrical testing of the basic thermoelectric couples was being done, a program for testing the mechanical strength of the legs of these couples in tension was carried out concurrently. These tests were performed at room temperature. Using these tests, various joining techniques were evaluated and a

choice made which insured that the weakest part of each leg was the thermoelectric material itself and not the joints. This work is also being continued as a method of both joint and pellet strength evaluation.

GENERAL DESCRIPTION

The generator and its basic components are shown in Figures 6 through 16. The combustion chamber is cylindrical, about 5-3/8" diameter and 10" long. The aluminum core which forms this chamber is made in three sections with mica inserts between them. This sectioning reduces the total axial expansion of the core relative to the cold side and consequently limits the stresses on the couples. The outside of the core is hexagonal, providing flats for the pressure mounting of thermoelectric modules against the heated surface.

The thermoelectric modules consist of 25 couples in a rectangular array (5 x 5) potted in an inorganic insulation. The flexible, electrically conducting heat exchangers are soldered directly to the couples to form a self-supporting module.

Pressure loading of the modules against the core is obtained by using springs on the tops of the heat exchangers compressed by a flat plate of aluminum honeycomb. In this unit the required force or constraint necessary for the pressure loading is supplied by a framework and end plates surrounding the core to which the honeycomb is bolted. In future designs, this structure would be eliminated to reduce weight and simple bands around the generator would be used to constrain the honeycomb plates.

Side rails attached to the honeycomb plates serve as ducting around the heat exchangers. This permits axial flow of the cooling air along the generator and minimizes the losses in the air flow path over other possible patterns.

A sheet metal transition piece is used between the vane-axial blower and the main part of the generator to reduce losses between the blower and the heat exchanger ducts. It also serves to hold the burner assembly and insulating block. In addition, a safety over-temperature shut-off valve in the fuel line is mounted in this transition piece; this valve has a temperature sensitive trip mechanism. The control circuitry for the blower is also mounted on this transition piece and utilizes it as a heat sink.

The weights of the various generator components are tabulated below:

TABLE II

Description	Quantity		Total Wt.	
Couples	450 @ .0220 lb.		9.9 lb.	
Heat exchangers			4.9	
Springs			.9	
Solder, insulation, etc.			.7	
Weight of modules (sum of above)	18	Sub Total		16.4
Core	3 sections		4.3	
Honeycomb plates and side panels	6		2.6	
End plates (2) and rails (6)			2.2	
Bolts, instrumentation thermocouples, etc.			1.3	
Weight of generator section	1	Sub Total		26.8 lb
Transition section	1		1.6	
Burner	1		.2	
Shut-off & safety valves	1 ea.		.1	
Insulating block	1		1.2	
Combustion screen	1		.8	
Blower and motor	1		3.9	
Control circuit	1		.5	
Gaskets, grill, etc.			.5	
Assembled generator		Total		35.6 lbs

HEAT EXCHANGER

Although the final heat exchanger design was dictated to a great degree by the couple geometry, the preliminary investigations and design work was done on a general "information gathering" approach to obtain data and heat transfer characteristics of many different heat exchanger geometries and designs so that an intelligent comparison of the different designs could be made.

Two parallel approaches were made to the problem. One approach was a straight forward engineering analysis of the heat transfer from a straight fin under forced convection. At the same time, experimental testing was done to verify the analytical heat transfer work. Since accurate prediction of system pressure drops and the effects of entrance and exit losses on air flow is very difficult, the experimental model was also needed to obtain this information.

Analytically, a differential equation for the temperature gradient along a flat rectangular fin was derived from which the heat flow into the base of the fin was determined. In this analysis, an average overall heat transfer coefficient was calculated on the basis of an assumed air flow which could be reasonably obtained with available blower systems utilizing the best state of the art in blower-motor design. More attention will be given to the blower-motor selection later.

Using this information, plots were computed for heat flux versus air flow for various fin base temperatures. Since weight was important, the effect of thickness and length on weight versus heat transfer was also determined. Primarily the analysis was used to give a firm basis on which to design heat exchanger test samples, although it should be expanded by computer techniques to incorporate a refined solution if further work and optimization is to be done on the generator as a system. However, sufficient design data was obtained by the aforementioned approach to permit the choosing of a satisfactory heat exchanger design.

As stated previously, a parallel experimental investigation of various compact heat exchangers was conducted to determine both heat transfer capabilities and air flow impedance with the heat dissipated per unit weight as the major parameter of concern.

All heat exchanger samples were tested in the arrangement shown in Figure 17. Electric heaters, press fit into a large aluminum block, served as the heat source for the various heat exchanger samples. The heater block was insulated against heat loss by an effective high temperature insulating material to insure minimum error (i.e., Min-K insulation). Each sample or model heat exchanger was bolted intimately to the heater block. In addition, a thermal conducting silicone grease was used between the sample and the heater block to insure maximum thermal contact and uniformity of heat flow. In this way, neglecting heat leak through the insulation, the heat into the sample heat exchanger could be determined by measuring the electric power into the heaters by means of a watt meter. Also, the heat flux could be controlled and varied by regulating the voltage to the electric heaters. Room temperature air was ducted to the sample testing section from a stationary supply blower, and flow straighteners and sufficient duct lengths were used to insure that fully developed laminar flow was present downstream from the sample section. This was done primarily to make flow measurements more accurate and easier to obtain. Flow measurements were made downstream by a standard pitot tube traverse across the air supply duct. Static and total pressure measurements were made at the entrance to the sample test section so that the entrance (sudden decrease

in cross section) and exit losses could be included in the overall pressure drop across the heat exchanger sample. Since these losses would in most cases be present in the actual generator system, their magnitude was of great interest. In addition, thermocouples were located in the air stream path to measure inlet, mean, and exit air temperatures at the sample test section.

Two different sample sizes were used in the heat exchanger testing. Initial testing was done with 6 inch x 6 inch square samples due to the availability of a test arrangement for this size. Subsequent testing was done with 9-1/2 inch x 4-5/8 inch size samples. The change in sample size was made to save design time and to include the effect of the temperature gradient and pressure drop along the heat exchanger length. This particular size was chosen since it approximated (at the time of testing) the expected dimensions of one side of the generator. The results of these tests on the final heat exchanger design are shown in Figure 18.

Once the flow characteristics of the heat exchanger design were determined and the operating heat flux level was set,(i.e., the total required air flow was determined) the next problem was that of obtaining a suitable blower motor unit. The design specifications were 400 CFM at 1 inch of water static pressure at minimum weight and power. A survey of commercially available blower motor units operating on direct current in the 12 volt to 28 volt range had been previously made. The overall efficiencies (air horsepower output/electrical power input) of such units were in general much lower than desireable for an application in which a severe penalty is paid for electrical power consumption. Consequently, a special blower was requested of several manufacturers to match the air flow requirements within the weight and power limitations imposed by the generator system. The overall efficiency was required to be greater than 50 per cent in order to meet the desired generator performance. To do this, blower and motor efficiencies of greater than 70% were necessary. In the designated range of operation, a vane axial blower is not only most efficient but also the lightest and smallest. In cooperation with the General Turbine Company, a lightweight vane axial blower-motor unit was designed, built, and tested. Its performance was within the design specifications required by the generator system. The final unit delivered 380 CFM at 1 inch of water static pressure, weighed 3.9 pounds (90% of which is motor weight) and required 80 watts at 20 volts. This unit came very close to the desired specifications and proved quite satisfactory.

CONTROL CIRCUIT

A control circuit (Figure 19) has been provided which protects the blower-motor from receiving an overvoltage. This is accomplished by placing a parallel combination of a resistor and a transistor in series with the motor as shown in the schematic. The resistance of this parallel combination can be varied continuously from some low value (essentially the forward resistance of the transistor) to some higher value (essentially the size of the parallel resistor) by turning the transistor from full on to full off in a continuous manner.

The power transistor (TR_1) receives base drive current from the emitter-collector circuit of TR_2. As long as V_1 is larger than V_2, transistor TR_2 will be on and TR_1 will conduct. If V_1 becomes less than V_2, TR_2 will turn off, depriving TR_1 of base current and causing TR_1 to turn off.

The voltage limit across the motor may be adjusted by varying R_3. As an example, suppose it is desired to limit the motor voltage to 24 volts. To do this, R_3 should be set approximately equal to R_4. As V_g increases from zero, V_1 will be approximately equal to V_g (since Zener diode impedance below 12 volts will be much greater than R_2) and V_2 will be approximately 1/2 V_g, TR_2 will conduct and consequently TR_1 will conduct. As V_g exceeds 12 volts, the Zener diode will maintain V_1 at 12 volts and V_2 will continue to rise as 1/2 V_g.

When the motor voltage begins to exceed 24 volts, V_2 will exceed 12 volts which will begin to turn off TR_2, initiating the turn-off of TR_1. Since the impedance of the parallel combination of TR_1 and R_1 increases as TR_1 turns off, an increasing amount of the input voltage, V_g, will be dropped across R_1, limiting the voltage across the motor. With R_1 approximately equal to the motor impedance, V_g must reach two times the rated voltage of the motor before any overvoltage is applied. Since the power transistor has a current gain of approximately 500 and a very low forward impedance, the control circuit absorbs a very small amount of power to perform its function.

The portion of the circuit in the dotted outline has been potted in epoxy and mounted on the outside of the blower ductwork. The control shaft of R_3 extends out of the epoxy and is convenient for adjustment. On the delivered generator this control is set to protect the motor at 24 volts. The power transistor TR_1 is mounted on the outside of the blower ductwork and the series resistor R_1 is epoxied to the inside.

BURNER DEVELOPMENT

The work effort on the burner problem as related to generator system operation actually involved two phases. The first was to investigate various types of burners and to choose a few which appeared to be most promising for this application. The second was to develop one of these into a burner capable of providing a thermal flux up to 80 watts/in^2 at 500°C with an efficiency greater than 50%. Noise level and infrared detectability were considered to be of secondary importance during the initial phase of the burner development, but compatibility with regard to burning either propane or gasoline was considered necessary.

Fuel Feed System

Since thermoelectric generators must be completely self-sufficient, every watt of auxiliary power consumed causes an increase in generator size and weight. Furthermore, this power is not available at start-up. As a result, it is desireable to have either manual or self-contained fuel pumping.

Propane presented the least fuel pumping problem since the 128 psi supply tank provides enough pressure (at room temperature) to overcome system resistance and give high enough nozzle velocities to inspirate sufficient air for proper combustion. For propane, the supply tanks provided flow by varying the burner orifice opening and the low side pressure through a regulator. For testing, a variable orifice nozzle (similar to a needle valve) was used at the base of a Meeker burner. It was found that by varying the pressure and nozzle openings the combination of higher pressures with smaller nozzle openings (between 25 psi and 35 psi) produced the highest heat fluxes at the best efficiencies. This was due to the higher nozzle velocities which caused a greater pressure drop in the throat of the venturi section, thus inspirating the necessary air for proper combustion, against a nominal back pressure in the combustion chamber.

Gasoline provided a somewhat more complex problem for fuel feeding since the system initially is at atmospheric pressure. Slight pulsation in the supply systems employing vaporizers rendered a flow meter useless for tests. Consequently, a special test fixture was constructed, similar to a Reid vapor bomb, for preliminary testing. The sealed unit was filled with liquid gasoline and placed on a scale gauged to one gram accuracy. A controlled electrical heater was used to provide the heat input necessary for obtaining the desired pressure. Thermocouples in the apparatus measured the temperatures inside the tank, and data was acquired for the flow rate of gasoline vapor as a function of temperature, pressure, and nozzle

opening. It was felt that this basic information was necessary before the system could be incorporated into a working burner design.

When the desired thermal characteristics of both systems (propane and gasoline) were finally obtained, the two fuel systems were investigated under simulated generator conditions. The transition from test setup to generator operation was no problem when propane was used since the mechanics of fuel feed and air injection remained the same.

Gasoline, on the other hand, presented several complications in this regard. Pressurization was obtained by using an air pump on an auxiliary tank to provide a driving pressure for the gasoline. A regulator was used to control the pressure supplied to a second tank containing the gasoline. This supplied relatively constant fuel pressure from full to empty. Further use of this air is made during start-up when some air is bled from the tank and injected into the fuel line to provide excess air during start-up, before the vaporizer is up to temperature.

Vaporization of the gasoline was obtained by passing the liquid fuel through constricted coils exposed to the heat of the combustion chamber. Although the vaporization system was workable, modification was necessary to eliminate the erratic series of pulsations which resulted in both extreme noise and carbon deposition. The fundamental cause of this pulsation is flame front instability resulting from a two phase ejection for the outlet nozzle: liquid droplets and vapor. Rather accurate control of the heat input to the vaporization coils is required to fully vaporize the gasoline without cracking the fuel. Insufficient time was available to develop an automatic control of the vaporizer temperature, but careful design did yield a model in which the pulsations were reduced to an acceptable level.

Testing Procedure

After development of the fuel systems, attention was given to the performance of the burner system in an actual combustion chamber simulating generator flux loading and geometry. This combustion chamber was constructed with 45 square inches of internal surface area. Insulated water jackets were fitted over the outside of the walls and thermocouples placed in the inlet and outlet flow streams. Since all of the heat passing through the core walls had to flow into the cooling water, the water temperature rise for a carefully measured liquid flow provided an accurate heat output metering device. The temperature of the combustion chamber (core) itself was monitored by means of thermocouples placed inside the core walls.

Tests were initially performed with high heat flux densities in mind. The evolution of internal screening began with a small inverted pyramid fitted with

an array of vertical screen fins. Previous screen core inserts used horizontal baffles which resulted in horizontal layers of hot spots. The baffles were changed to align in a vertical direction which resulted in a more even temperature distribution, but a significant percentage of the heat was still being lost up the stack as exhaust waste gases. The next sequence of tests used a small inverted pyramid configuration to spread the hot gases outward and to provide more convective action as well as force more hot gases through the screen, producing higher screen temperatures.

A thin wall (30 mils thick) core blaster was designed to produce an isothermal condition from combustion chamber bottom to top. A slight taper was built into the design to provide greater hot velocities at the top and hence greater heat transfer by convection. This compensated for the greater radiation heat transfer inherently at the bottom of such a system.

In operation, both the screen surrounding the core blaster as well as the core blaster itself became incandescent, the temperatures ranging from 2600°F at the inlet. The screen temperature averaged approximately 2000°F from top to bottom.

The high radiant and convective heat transfer resulted in heat flux densities between sixty and seventy watts per square inch at efficiencies of greater than 50%. One drawback to such a high flux system, however, was the noise level. It must be realized that the thermal output of the system approached the output of a home furnace in a core measuring only 4-1/2 x 4-1/2 in cross sectional area.

The noise was eventually reduced by increasing the cross-section of the burner grid and reducing the flame and gas inlet velocities. This reduced the flame front instability that was the main cause of the noise.

The second configuration that was tested using both gasoline and propane burner system consisted of a vertical screen array. This arrangement was initially investigated with catalytically coated screen, but testing indicated that plain uncoated screen would serve the same function.

Various screen densities were tested and different types of materials were used. It was found that 40 mesh screen proved the most acceptable from radiation and screen rigidity standpoints. Chromel-A screen proved to be very chemically active with the sulfur in the combustion gases which reduced the screen's effective service temperature and resulted in ultimate corrosion and destruction. Inconel was found to be impervious to the chemicals present and was used in the final burner screen design of the demonstration unit.

Generator System

Although the basic gound work on gasoline was completed , two primary problems forced the final generator design to be a propane system utilizing the Inconel vertical screen arrangement previously discussed. These two problems were: compact packaging of the system and insufficient control of the vaporizer temperature. Although it was felt that continued work would provide a satisfactory solution to these problems, time dictated the use of the more simple and reliable propane system so that the main goal of providing a lightweight portable generator could be met on time.

Although the propane system presented far less problems and had been tested to a greater degree, the inherent uneven flux loading in generator operation forced the final screen adjustments to be made in the actual finished generator to obtain the desired uniformity of core temperature. Minor changes were made during the preliminary testing period and the final design performed well in the qualification tests. However, some further modifications in the screen design would be necessary because of the variation of thermal flux in the axial direction if burner efficiencies above 50% are to be obtained.

GENERATOR TESTING

The fully assembled thermoelectric generator was tested under laboratory conditions to determine overall system operating characteristics as outlined in the contract specifications. However, the testing was somewhat more comprehensive than outlined in the contract requirements, since an effort was made to obtain data and information that would be helpful and valuable in the design and construction of future portable generators. In this way, the information gained by testing this first attempt at lightweight, high-power generator contributes more fully to extending the technology of thermoelectricity.

From a system standpoint, the testing also served a multipurpose function. Due to the nature of the burner-combustion screen, final adjustments and changes of the screen had to be made during initial generator testing. Also, trial and error testing was required to locate the point of maximum net power output so that the generator as a system could be optimized. And finally, the blower control circuit required final adjustment once the optimum operating voltage for the blower was found.

Test Arrangement

The generator was designed to incorporate temperature indicating thermocouples and voltage taps for each individual module, although it was realized that such instrumentation would not be necessary in a field device. The laboratory approach (instrumentation and control) was used so that as much information as possible could be recorded in a limited amount of testing time. For this reason, six (6) hot core thermocouples, fourteen (14) cold junction thermocouples, and eighteen (18) voltage taps were monitored. In addition, thermocouples were placed in strategic locations to measure structure temperatures and exhaust air temperatures. These thermocouples were used only during preliminary testing and they are not included in the final unit.

The ratio of energy output to total energy input was computed from test measurements in order to determine overall system efficiency. The energy (heat) input was determined by measuring the total fuel rate by means of a volumetric flow meter. Generator power output delivered to a matched resistive load was measured. This matched load was obtained by loading the generator to an output voltage of one-half of the open circuit value, the open circuit being measured instantaneously.

Additional measurements were made of blower speed using a standard Strobatac. Blower motor voltage and current were also measured. All temperature readings were recorded on a multi-point strip chart recorder and electrical measurements made with 1/2% accurate D.C. volt meters and ammeters.

Test Procedure

Although power tests were performed at various percentages of maximum operating temperature, the voltage requirements of the blower motor are such that a load cannot be applied until at least 85% of maximum temperature is reached. At low temperatures, the generator is supplying ample power for blower operation but a minimal or slightly less than necessary motor voltage. Any load at these levels, therefore, reduces the voltage and can raise cold junction temperatures dangerously close to the solder melting point. This situation would be alleviated in the future by using a blower motor requiring less operating voltage and designing the generator for higher allowable cold side temperatures.

In all preliminary tests to determine optimum operating conditions and to make the necessary burner and screen adjustments, an external D.C. power supply was used to operate the blower motor. During these tests, the blower motor voltage was adjusted to match the generator voltage which was open circuit in this case.

This at least assured stable operation of the generator as a self-contained unit, unloaded.

These preliminary tests were used to find the proper voltage tap on the generator to provide power for the blower motor. Power taps were available between each pair of modules in the generator. These tests indicated that the full voltage developed by the generator while loaded would be necessary for the blower motor to provide sufficient cooling at maximum temperature (hot side).

For maximum power tests (rated condition) no external power source was used and both generator and motor voltage were determined solely by the hot side temperature and resistive loading. The power delivered to the load now was the net power developed by the generator, that is, the total power developed less the power being taken by the blower motor.

The optimum operating point was found by varying the load and fuel rate in such a way as to keep the hot side temperature constant at the desired value while measuring the power delivered to the load. The point where the power delivered to the load passes through a maximum was called the optimum operating point. It should be noted here that the optimum operating point will be a function of generator internal resistance. During qualification tests at New Products Laboratories, this optimum point occurred when the generator was loaded to deliver 20.8 volts to the load while operating at rated core temperature (516°C average).

Results

The curves presented here were plotted from data obtained during qualification tests of the generator at the New Products Laboratories.

Figure number 20 shows the generator open circuit voltage as a function of <u>average</u> core temperature. To obtain this data, the blower motor was powered by an external source whose voltage was adjusted to be equal to the measured open circuit voltage up to a point in temperature where the generator voltage reached 20 volts. From this point on, the blower motor voltage was maintained at the 20 volt level, simulating the operation of the blower motor control circuit.

Figure no. 21 shows the voltage - current characteristics of the thermoelectric elements of the generator. For this information the blower was externally powered in the same manner as outlined previously.

The power generating capabilities of the generator as a self-contained system (i.e., blower motor powered by generator) is illustrated in Figure 22.

Overall system efficiency (including burner efficiency) is plotted in Figure 23. Again, net results can only be plotted for the temperature range about 85% rated temperature.

A comparison of calculated versus experimental results for this generator performance at maximum power is given in Table IV. The thermal flux, as shown, was quite close to the predicted values and within the experimental error. The power output of the couples over this temperature interval, however, was considerably below expectations due to high internal resistance as discussed previously. This, of course, reduced the expected thermoelectric efficiency as well as power output. The burner efficiency was also somewhat below expectations but experimental tests have shown that this can be raised to the predicted level by minor modification of the internal screen design.

	Actual Generator Test Results	Expected Value Based on H.E. Data and Fuel Consumpt.	Expected Value Based on Actual Couple Tests	Expected Values Based on MTLS. Data and Component Performance
Heat Flux hot side (watts/couple)	17.0	---	17.8	17.9
cold side (watts/couple)	16.3	16.8	16.7	16.2
Couple Output (watts)	.74	---	1.07	1.11
T/E Eff. (%)	4.4	---	6.0	6.2
Generator Output Watts (gross)	335	---	482	500
Generator Output Watts (net)	267	---	417	430
Specific Power (watts/lb.)	7.5	---	---	12.3
Burner Eff. (%)	39	40	---	55
Burner Heat Flux (watts/in^2) (based on core area)	51	---	---	54
Thermal Input Watts	19,600	---	---	14,700
Overall Efficiency (%)	1.4	---	---	3.3

Note: Performance for temperature interval of 450°C to 136°C

COMPARISON OF EXPERIMENTAL VS. CALCULATED
PERFORMANCE OF GENERATOR

TABLE III

CONCLUSIONS

The thermal performance of the back-pack generator was more than adequate, although certain modifications would be made in future designs. These modifications would include operation with a slightly lower air flow to reduce noise and slight alteration in combustion chamber baffle design to improve burner efficiency.

A realistic weight reduction of 4.0 pounds can be made in the present structure weight by using banding rather than a frame to contain the honeycomb plates, by reducing core wall thickness, and by replacing the insulating block around the heater with a less dense insulation. This weight reduction would permit the inclusion of approximately ninety more thermocouples with a corresponding increase in potential power output of 20 percent. With this modification, a couple having a 1.1 watt power output would permit a design weighing 35 pounds having a net power output slightly in excess of 500 watts.

The actual specific power of the generator is 7.5 watts per pound, the highest achieved to date. A specific power of 15 watts per pound is within reach for future back-pack generators. Tests have indicated that thermocouples can be constructed that will operate in air with hot junction temperatures of 450°C for one thousand hours or longer, making possible the construction of unsealed thermoelectric generators for military portable power source applications.

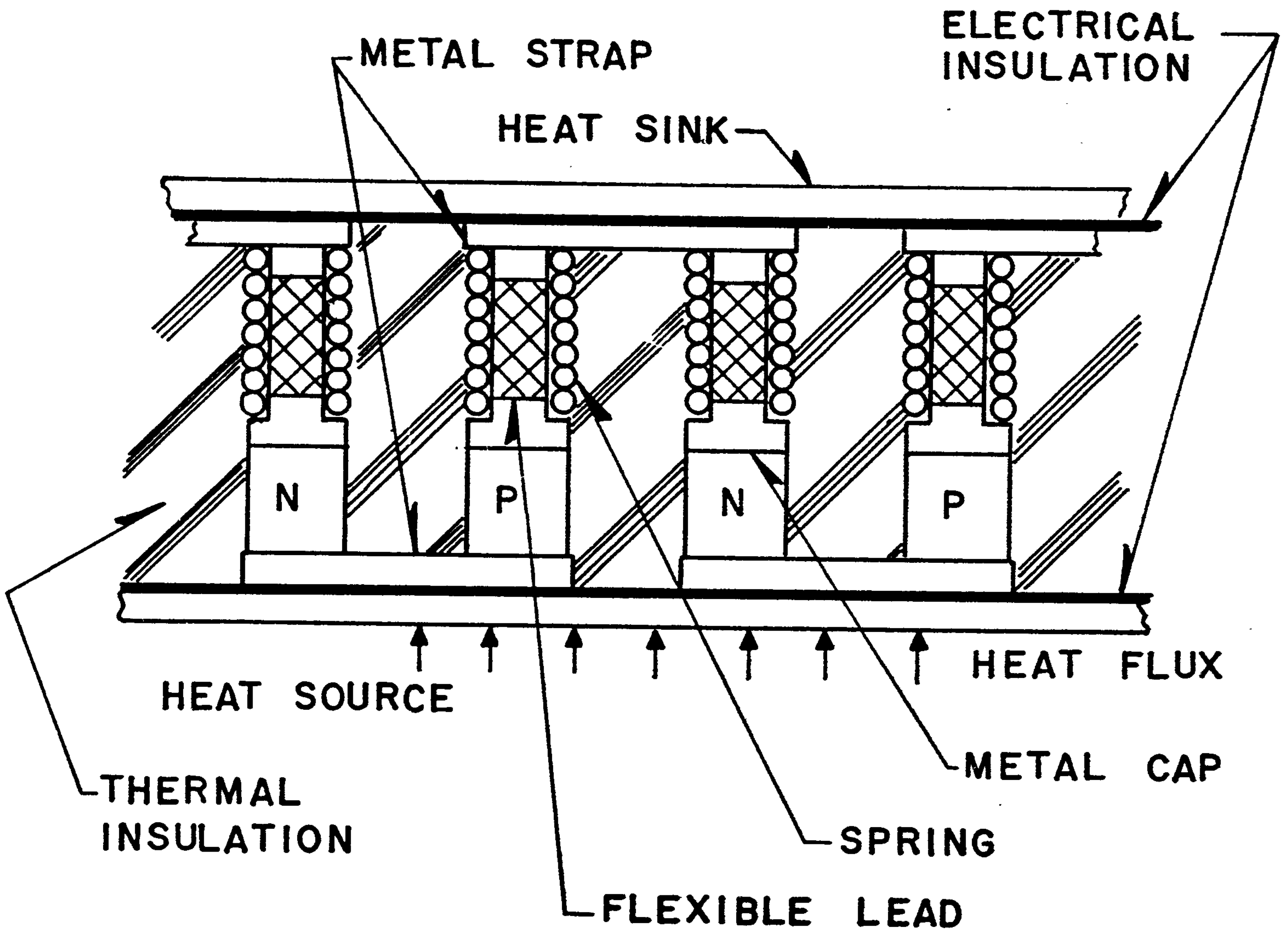
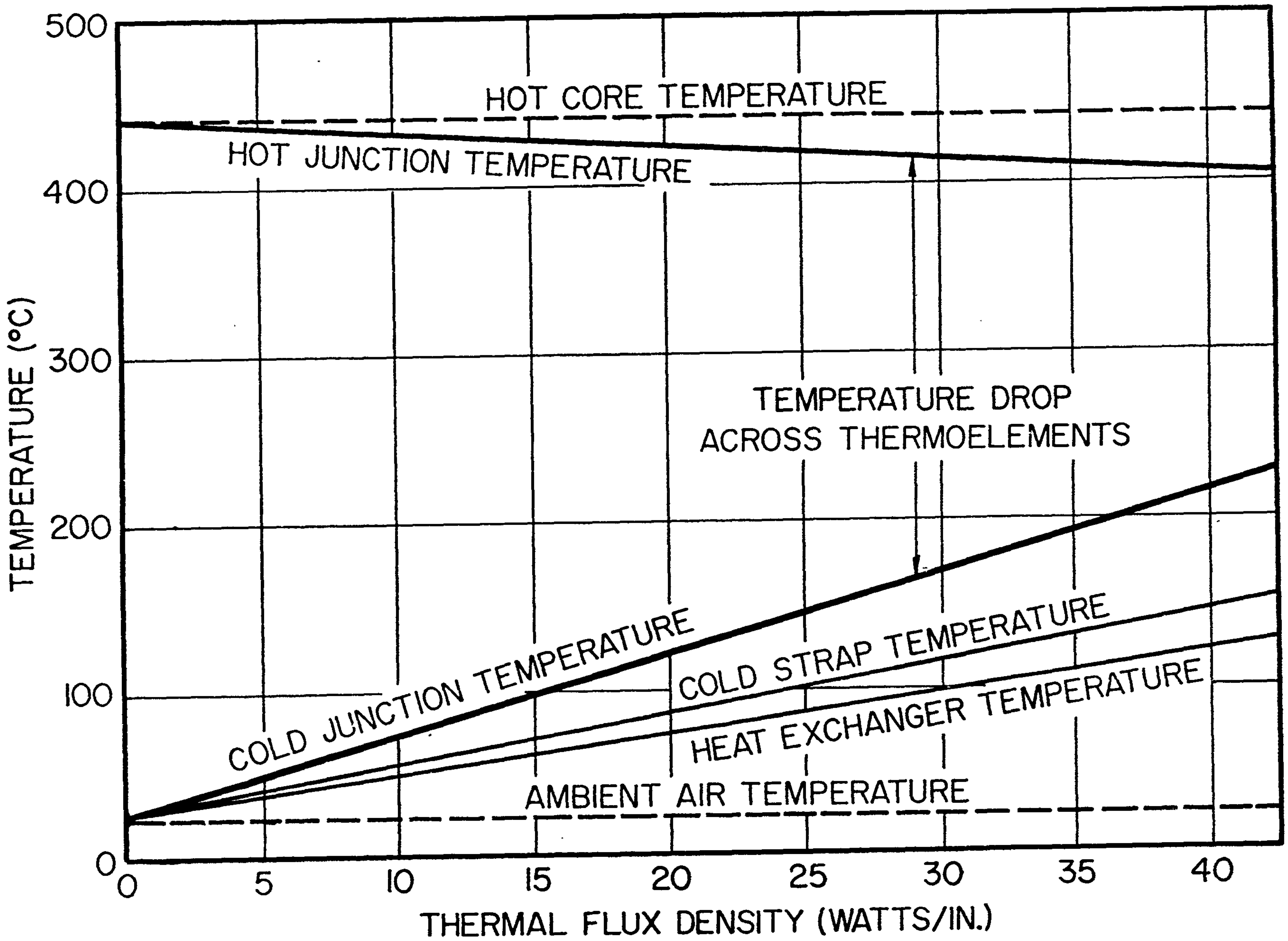

METAL STRAP
ELECTRICAL INSULATION
HEAT SINK
N
P
N
P
HEAT SOURCE
HEAT FLUX
THERMAL INSULATION
METAL CAP
SPRING
FLEXIBLE LEAD

FIG. 1



HOT CORE TEMPERATURE
HOT JUNCTION TEMPERATURE
TEMPERATURE DROP
ACROSS THERMOELEMENTS
COLD JUNCTION TEMPERATURE
COLD STRAP TEMPERATURE
HEAT EXCHANGER TEMPERATURE
AMBIENT AIR TEMPERATURE
TEMPERATURE (°C)
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
THERMAL FLUX DENSITY (WATTS/IN.)

FIG. 2

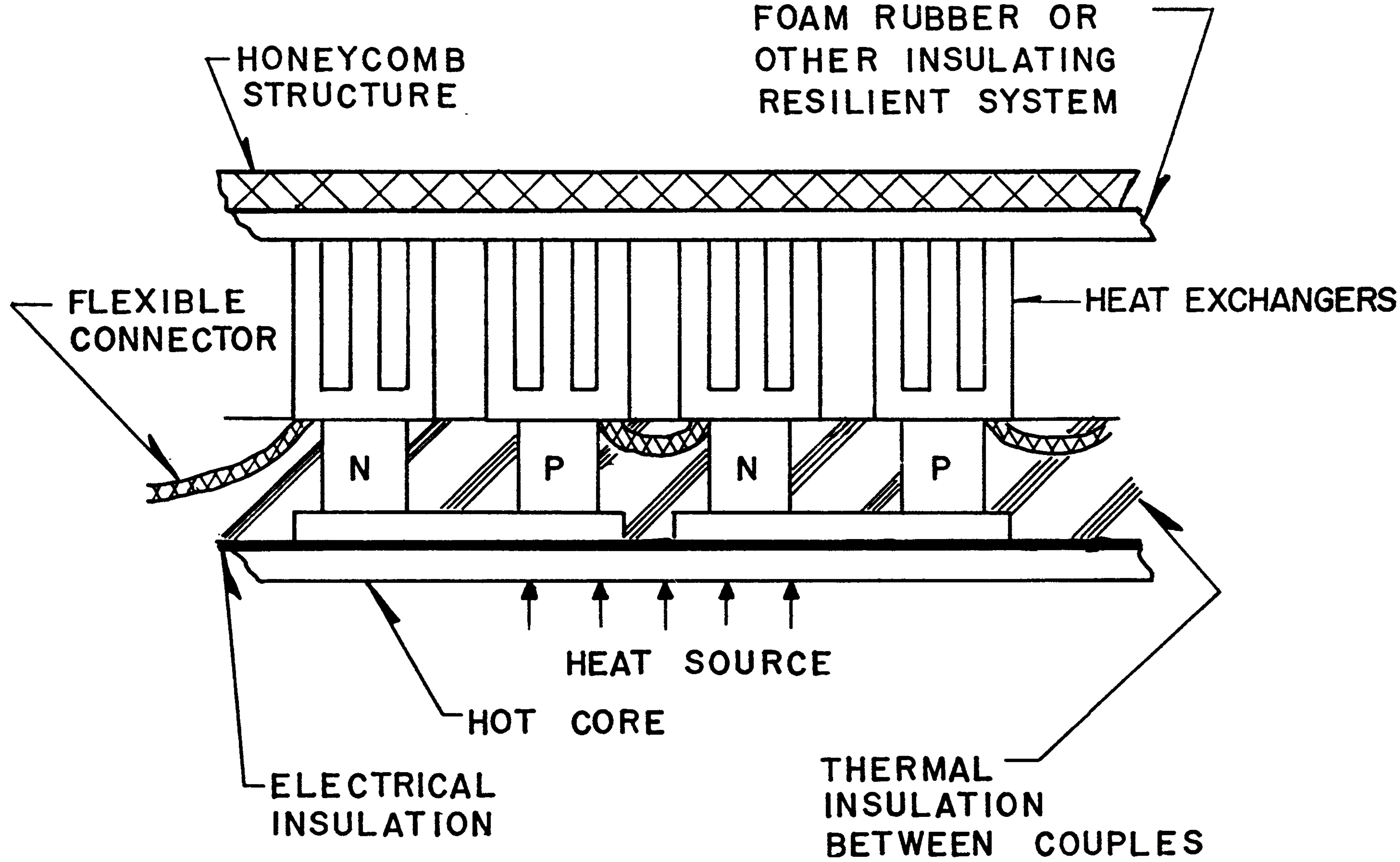

HONEYCOMB STRUCTURE
FOAM RUBBER OR OTHER INSULATING RESILIENT SYSTEM
FLEXIBLE CONNECTOR
HEAT EXCHANGERS
N
P
N
P
HEAT SOURCE
HOT CORE
ELECTRICAL INSULATION
THERMAL INSULATION BETWEEN COUPLES

FIG. 3

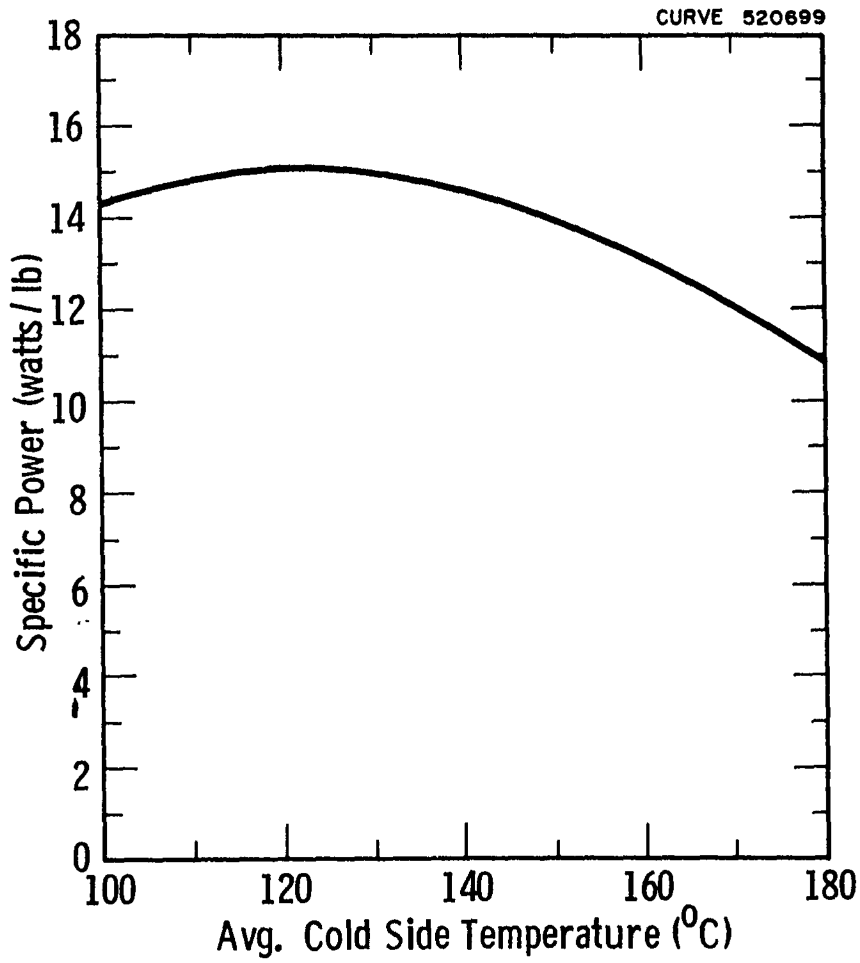

CURVE 520699
Specific Power (watts/lb)
18
16
14
12
10
8
6
4
2
0
100
120
140
160
180
Avg. Cold Side Temperature (°C)

Fig. 4

DWG. 623A170

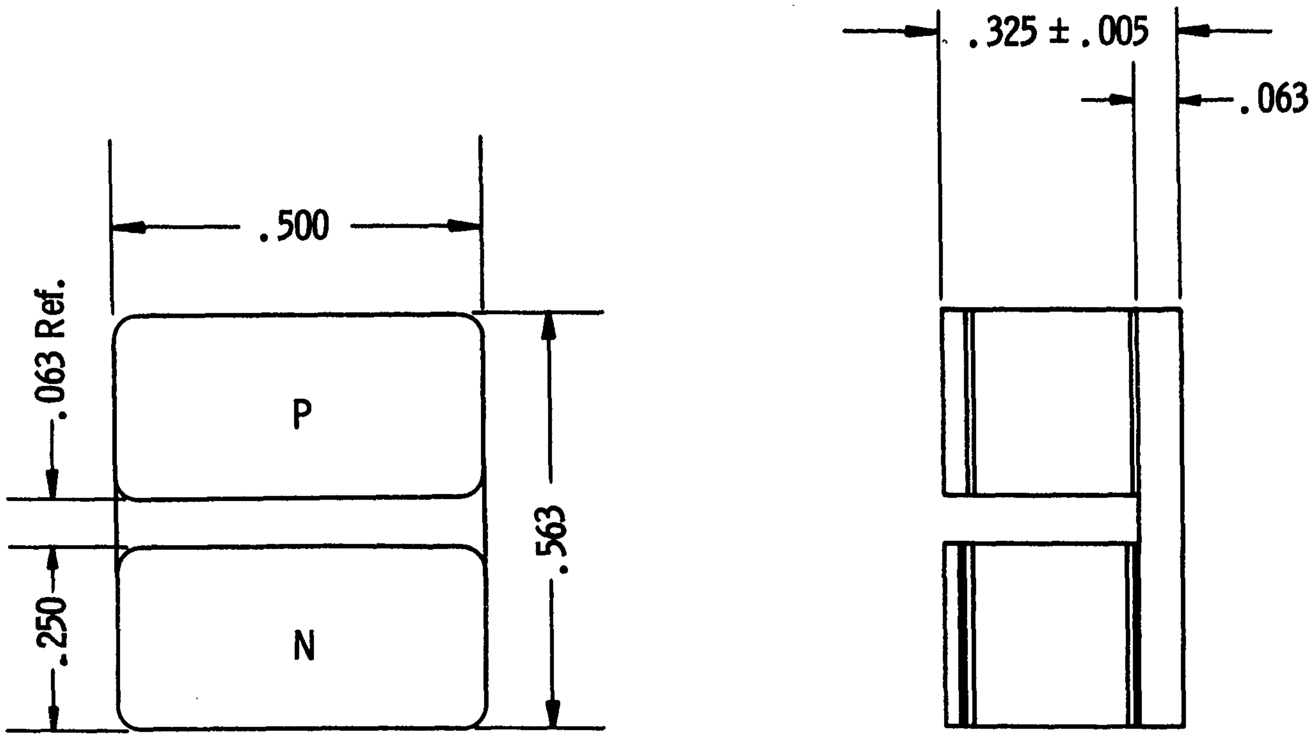


Fig. 5—Geometry of couple used in generator

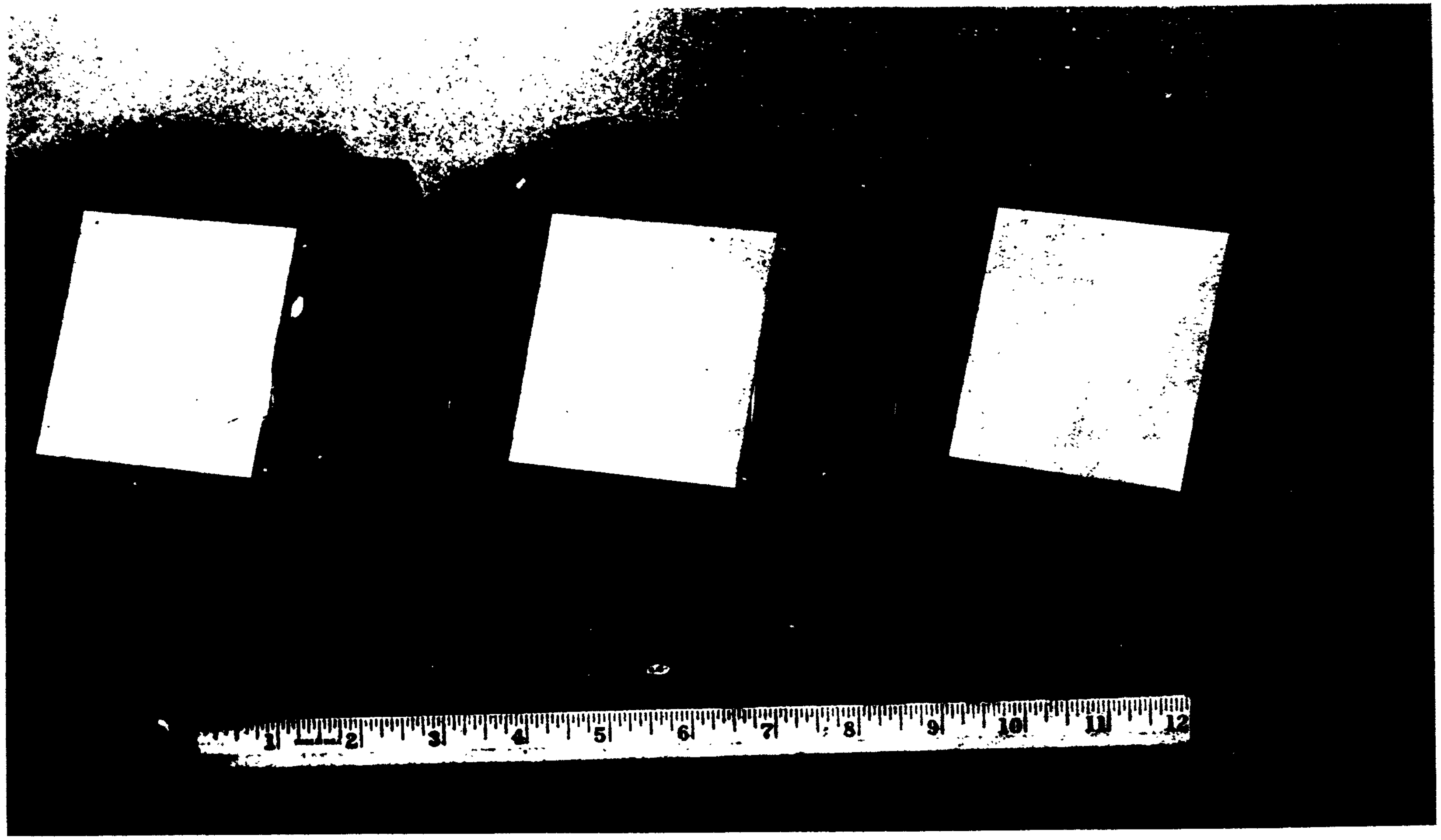


FIGURE 6: Exploded view of aluminum core used in experimental generator showing the three sections and the mica ring used between them to prevent gas leakage between the combustion chamber and modules.

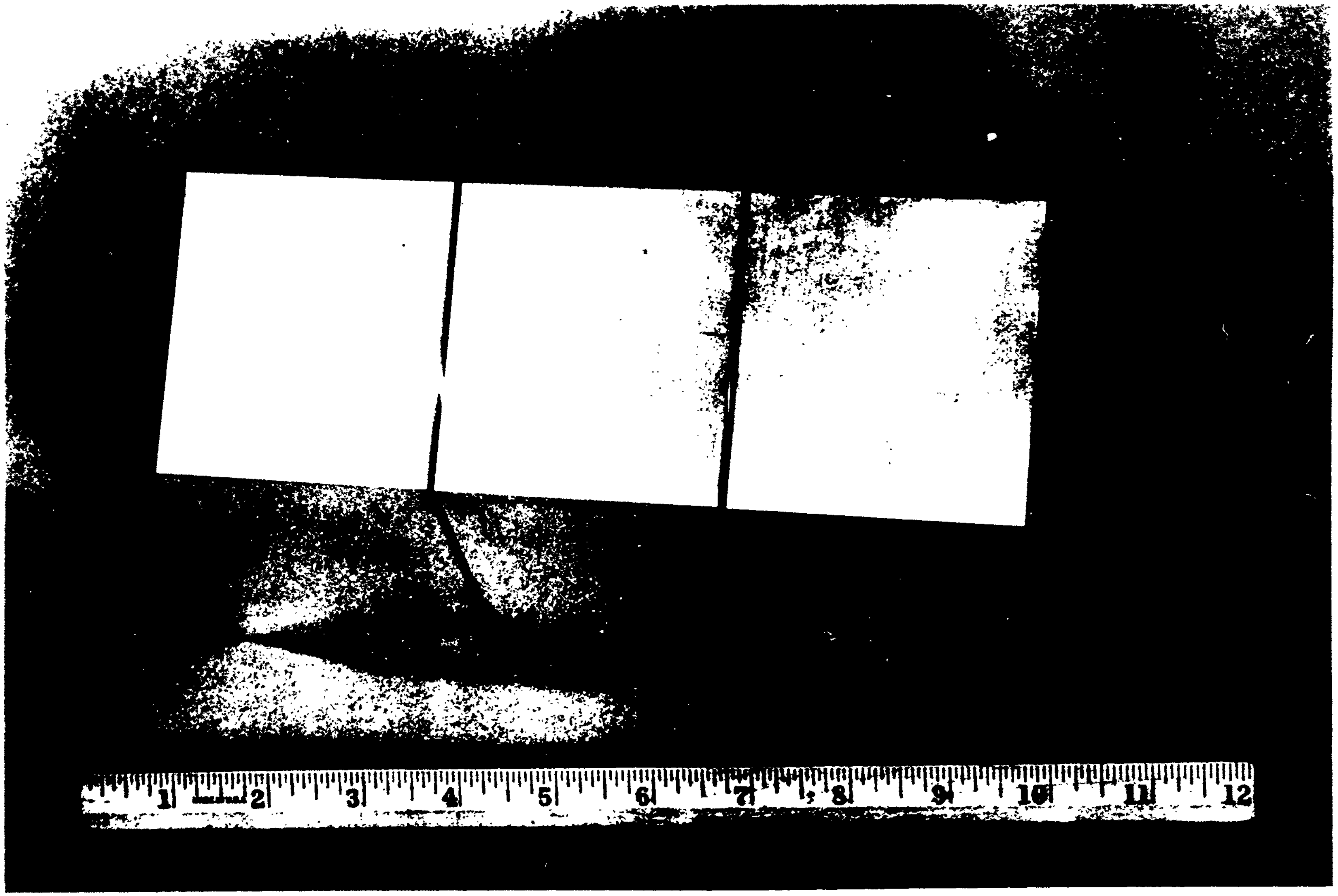


FIGURE 7: Assembled view of the core showing the spacing between the sections to allow for thermal expansion.

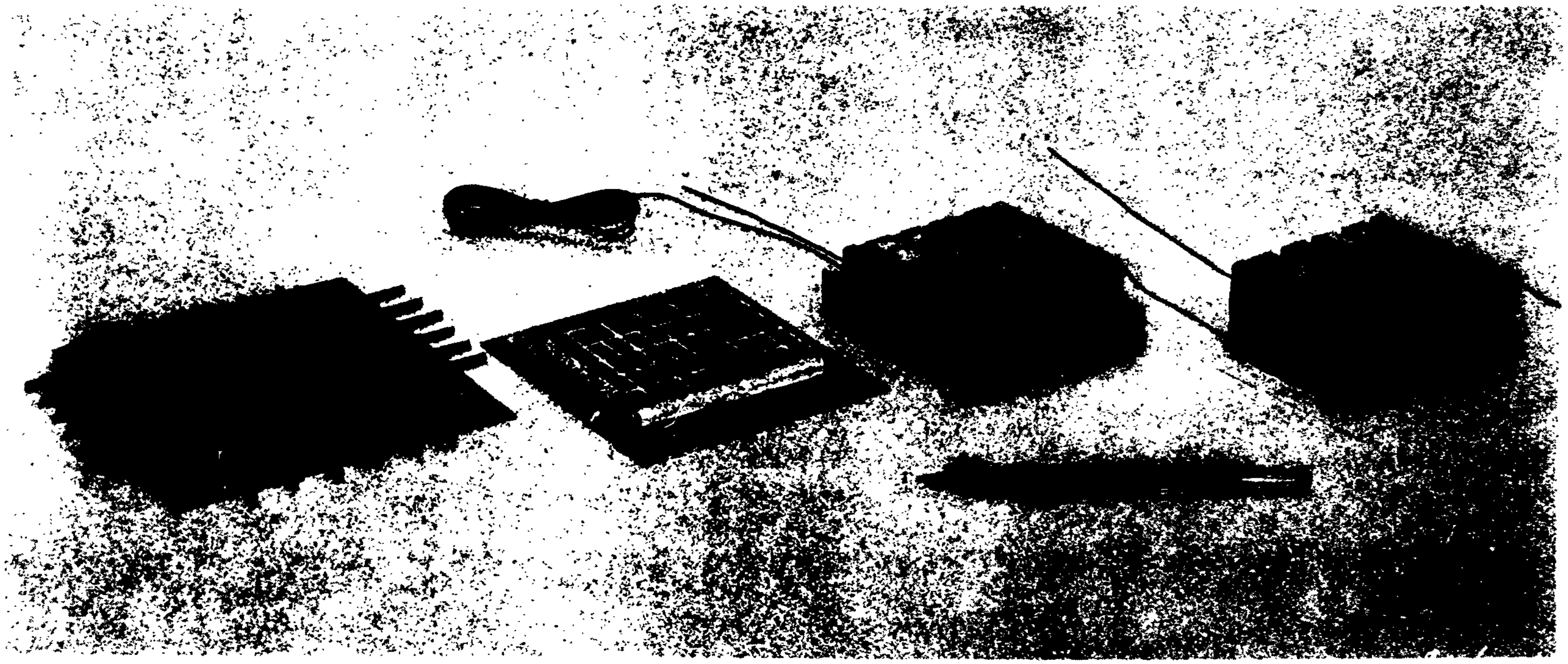


FIGURE 8: This photograph shows the simple potting jig used to align couples during assembly, an insulated couple module, the holding jig for the heat exchangers, and a soldered module ready for insertion in the generator.

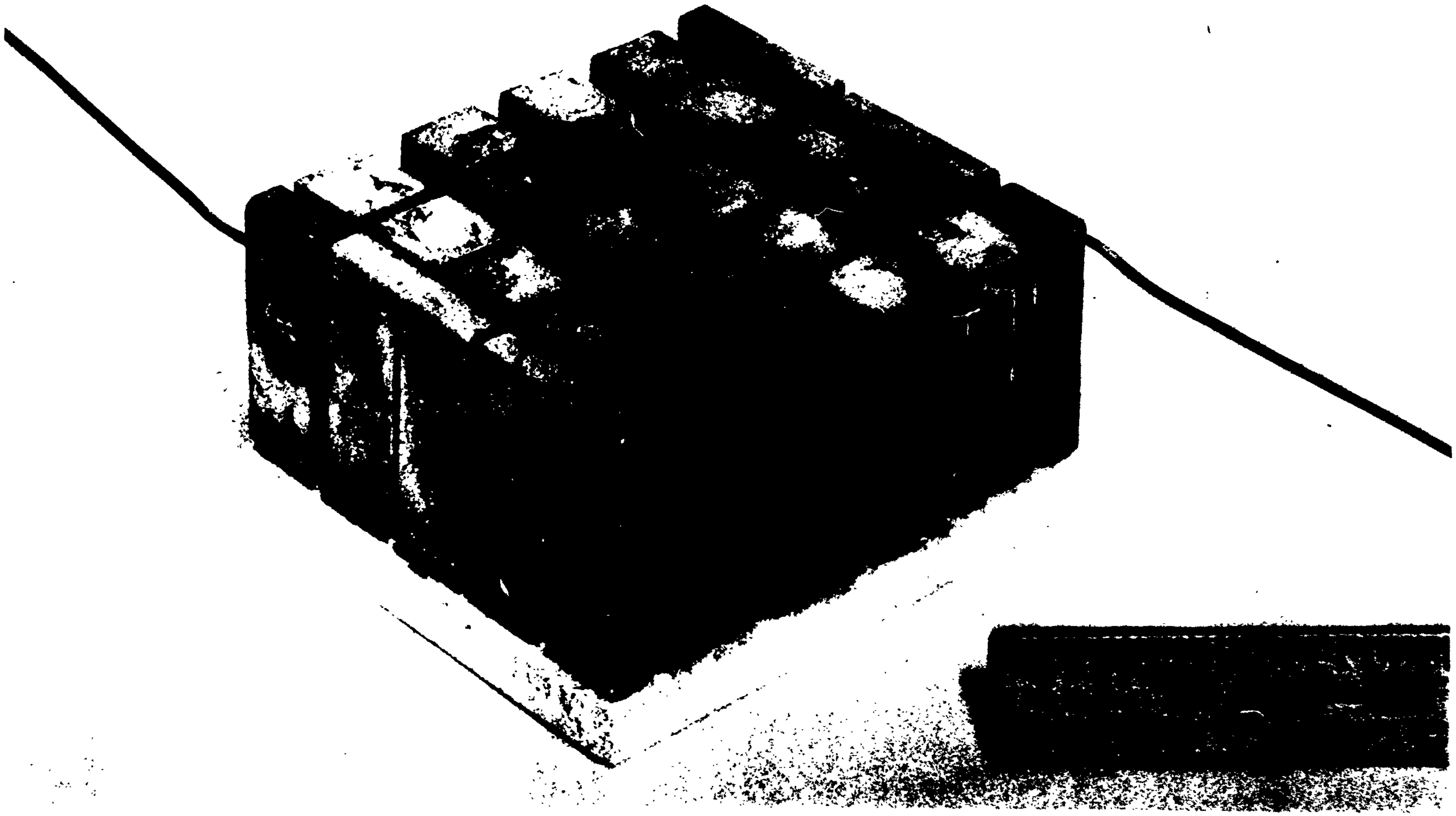


FIGURE 9: Close-up view of assembled module. It should be noted that the heat exchangers used in this experimental generator were hand fabricated and presented some difficulty as far as maintaining tolerances are concerned. However, the basic shape is easily extruded; this would appreciably reduce cost, facilitate assembly, and provide a lower pressure drop for the cooling air.

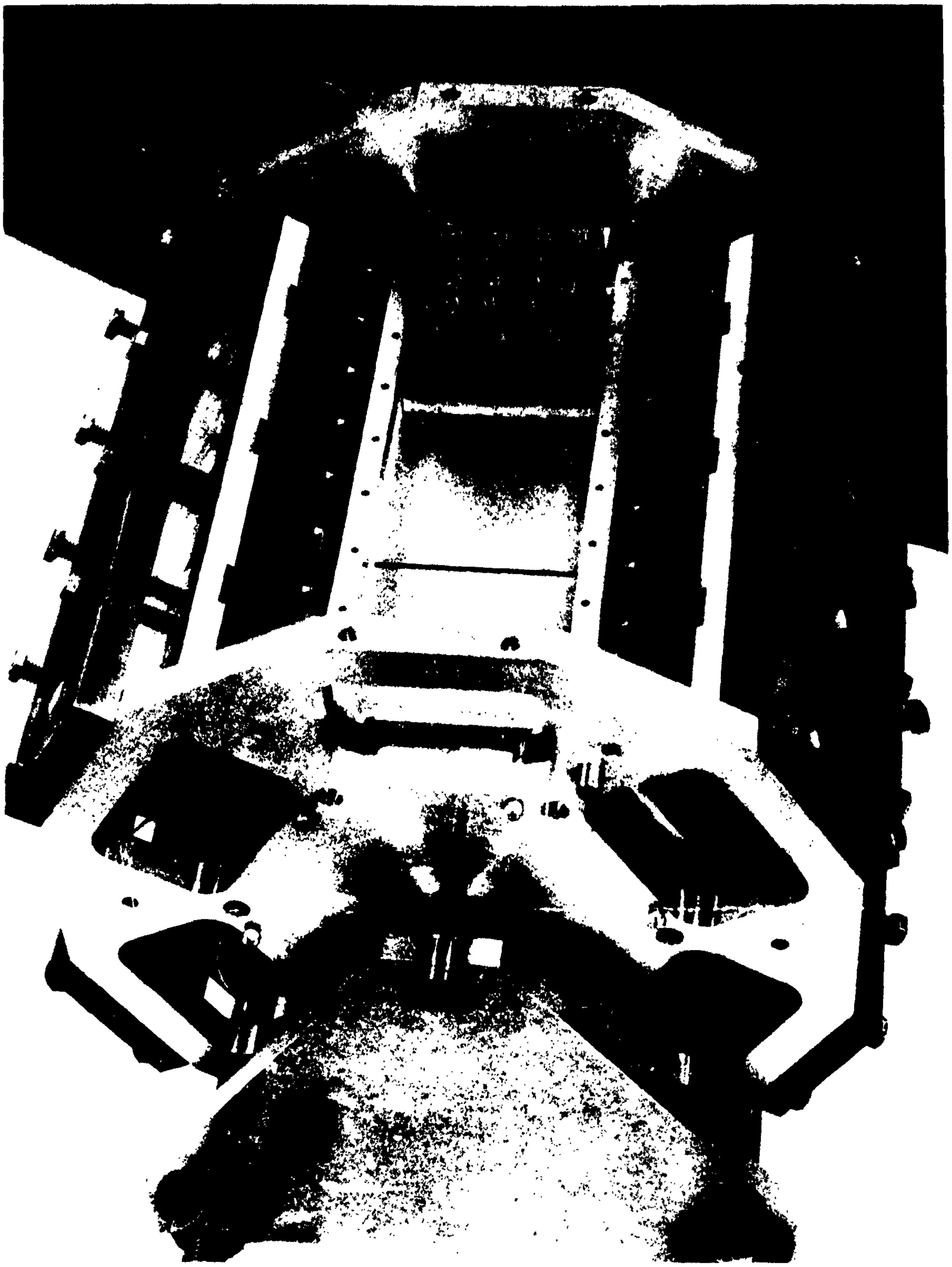


FIGURE 10: This photograph shows the assembly fixture used in fabricating the generator and the first module of a flat in place with the springs epoxied to the heat exchangers.

FIGURE 11: The final step in the assembly of a flat is the fastening of the honeycomb back-up plate. This compresses the springs on top of the heat exchangers and provides the necessary contact pressure to the heat source.

FIGURE 12: This photograph is an end view of the generator section showing the air path through the heat exchangers and the various instrumentation thermocouples used to determine heat exchanger and structure temperatures.

FIGURE 13: This photograph shows the basic subassemblies of the experimental generator: the generator section, the combustion chamber screen baffle, the transition section containing the burner, and the motor-blower.

FIGURE 14: Another view of the basic subassemblies of the experimental generator.

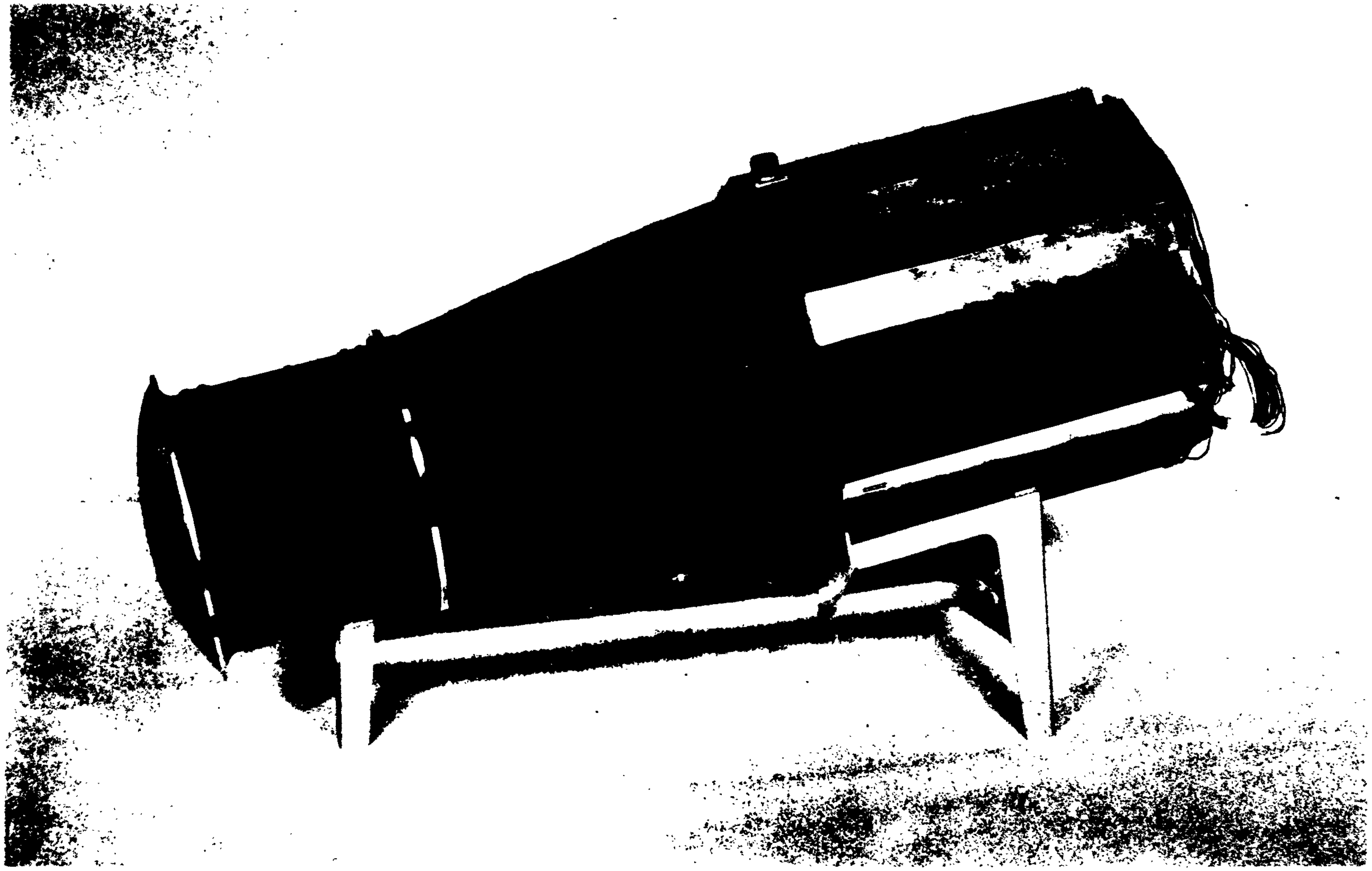
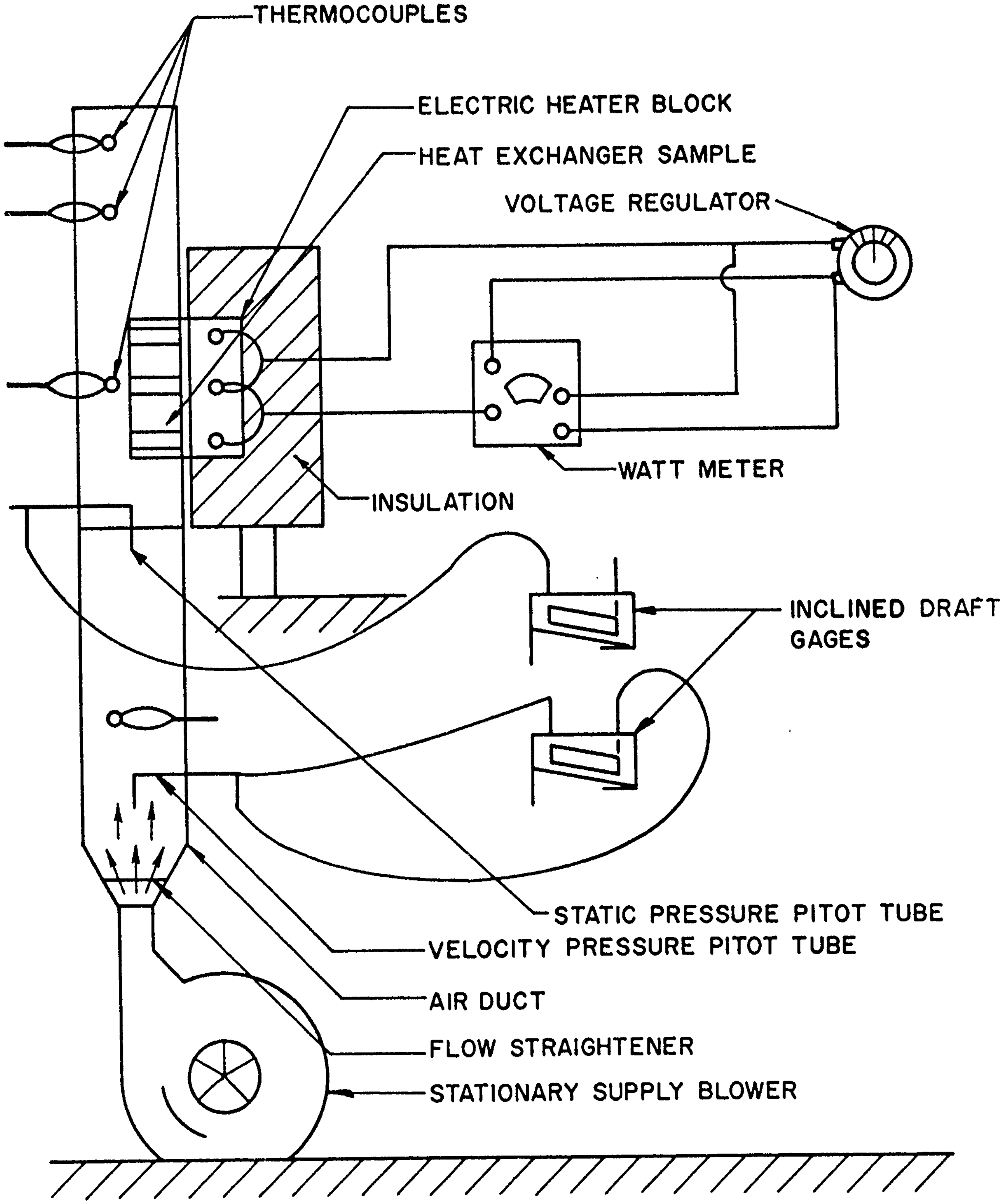


FIGURE 15: Side view of assembled experimental generator mounted on demonstration base.

FIGURE 16: Three-quarter view of assembled experimental generator.



HEAT EXCHANGER TEST ARRANGEMENT

FIG. 17

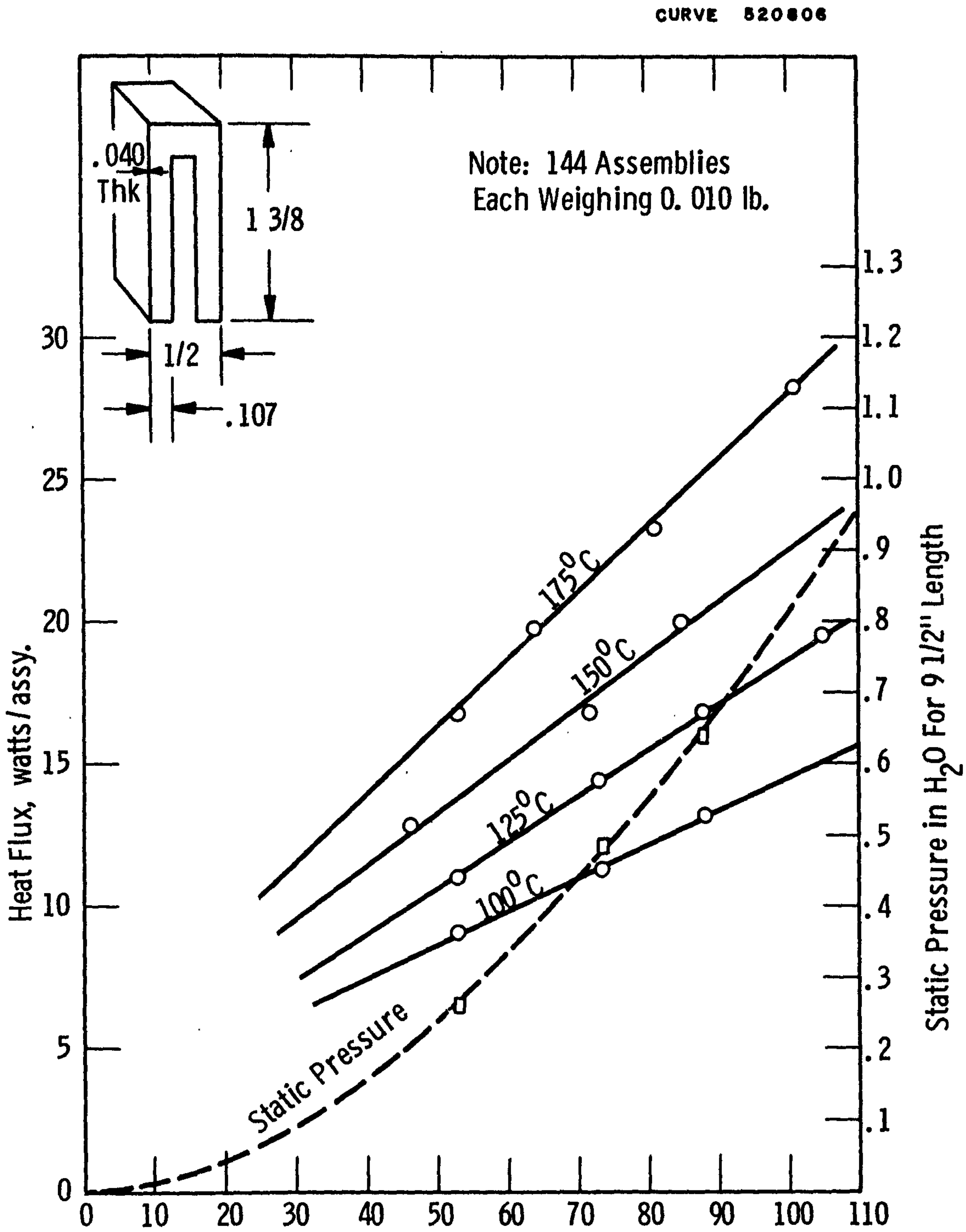
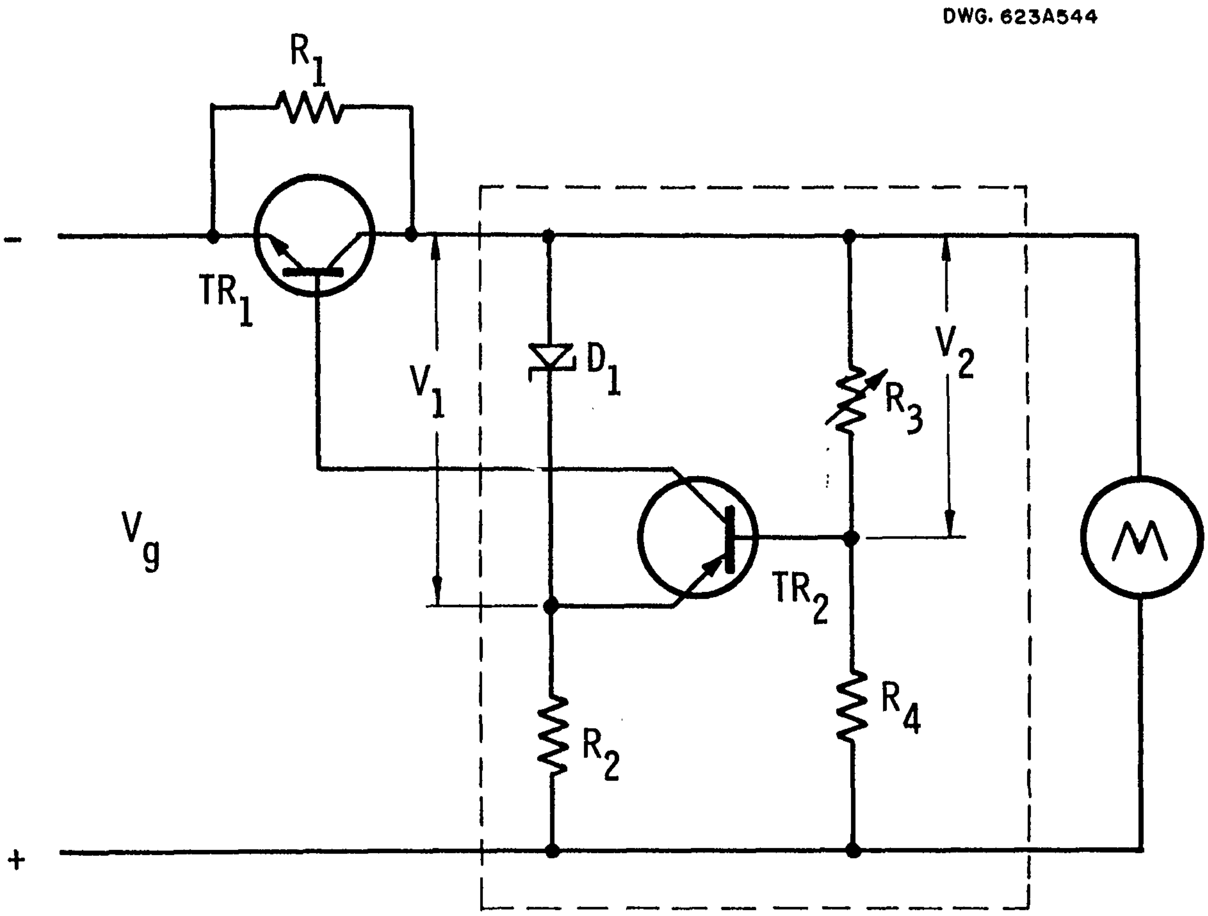


Fig. 18—Experimental results of tests on heat exchanger used in generator.
(For 9 1/2" long by 4 5/8" wide sample)



R_1	4 - 100 watt
R_2	500 - 1/2 watt
R_3	500 variable - 1/2 watt
R_4	150 - 1/2 watt
TR_1	WX118XA Westinghouse Power Transistor NPN
TR_2	2N652 Motorola PNP
D_1	12 V Zener Diode

Fig. 19— Blower motor control circuit schematic

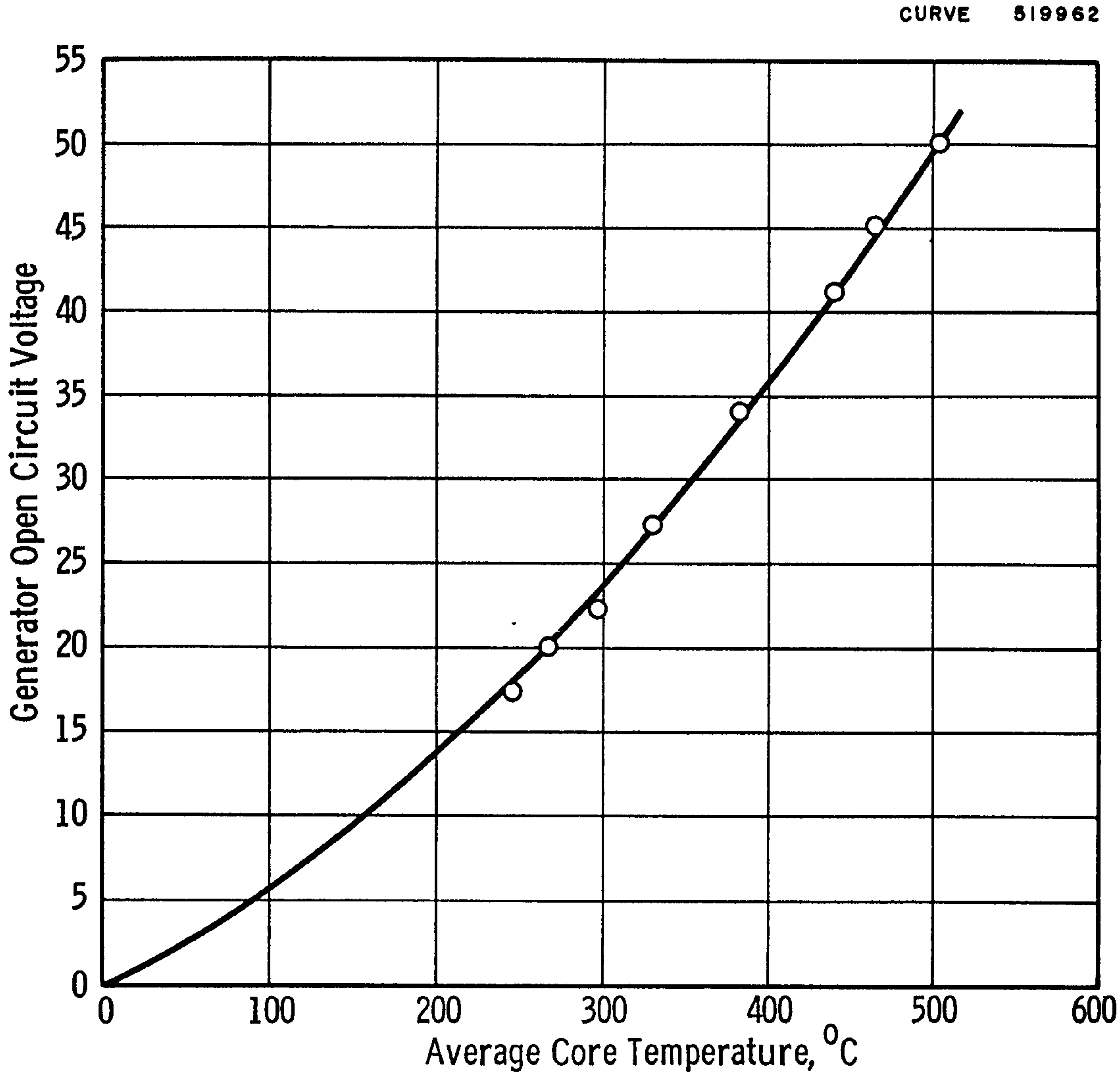


Fig. 20—Generator open circuit voltage vs. average core temperature

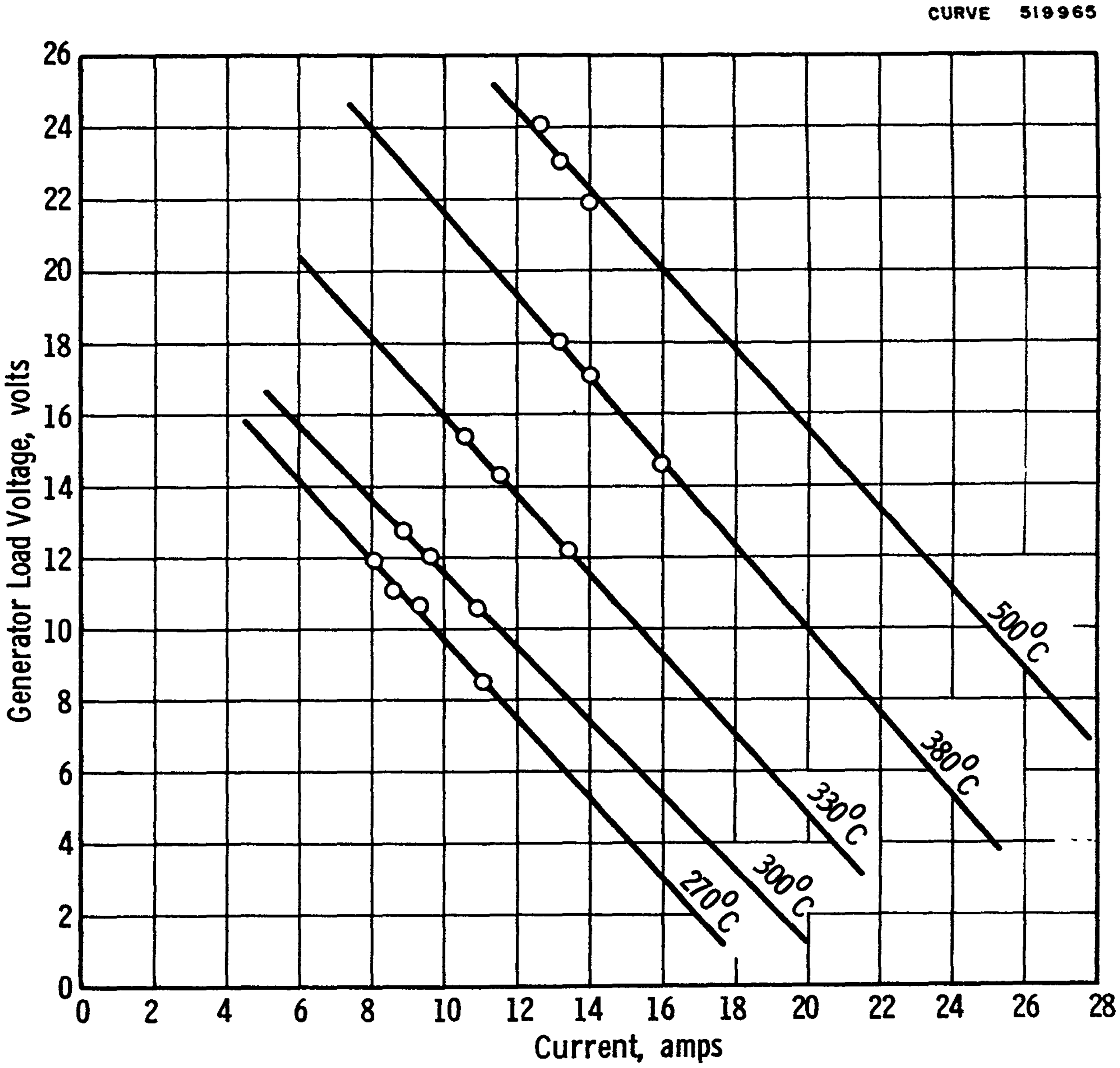


Fig. 21—Voltage vs. current at various hot core temperatures
(Blower externally powered)

CURVE 519964

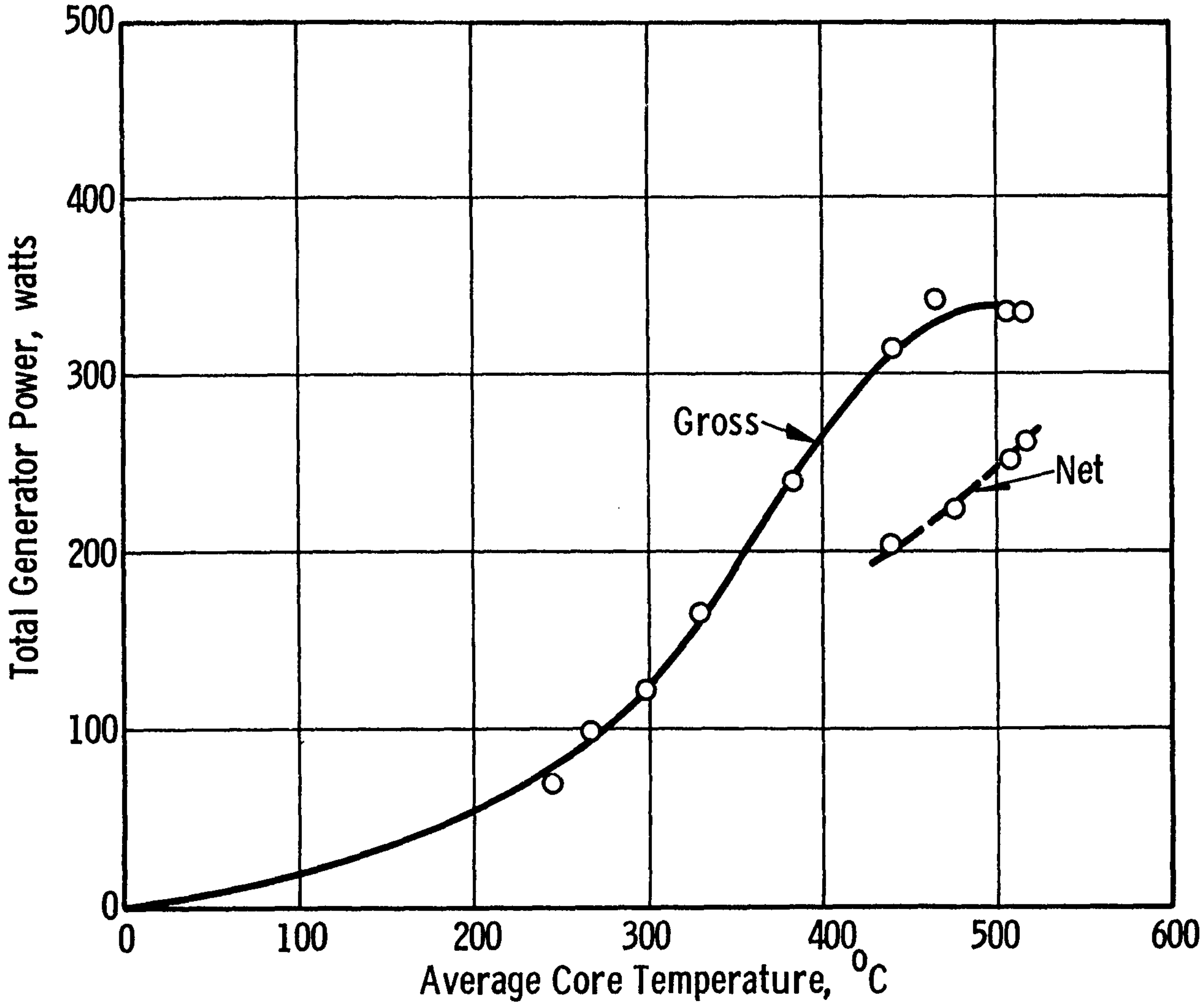


Fig. 22— Generator power vs. hot core temperature

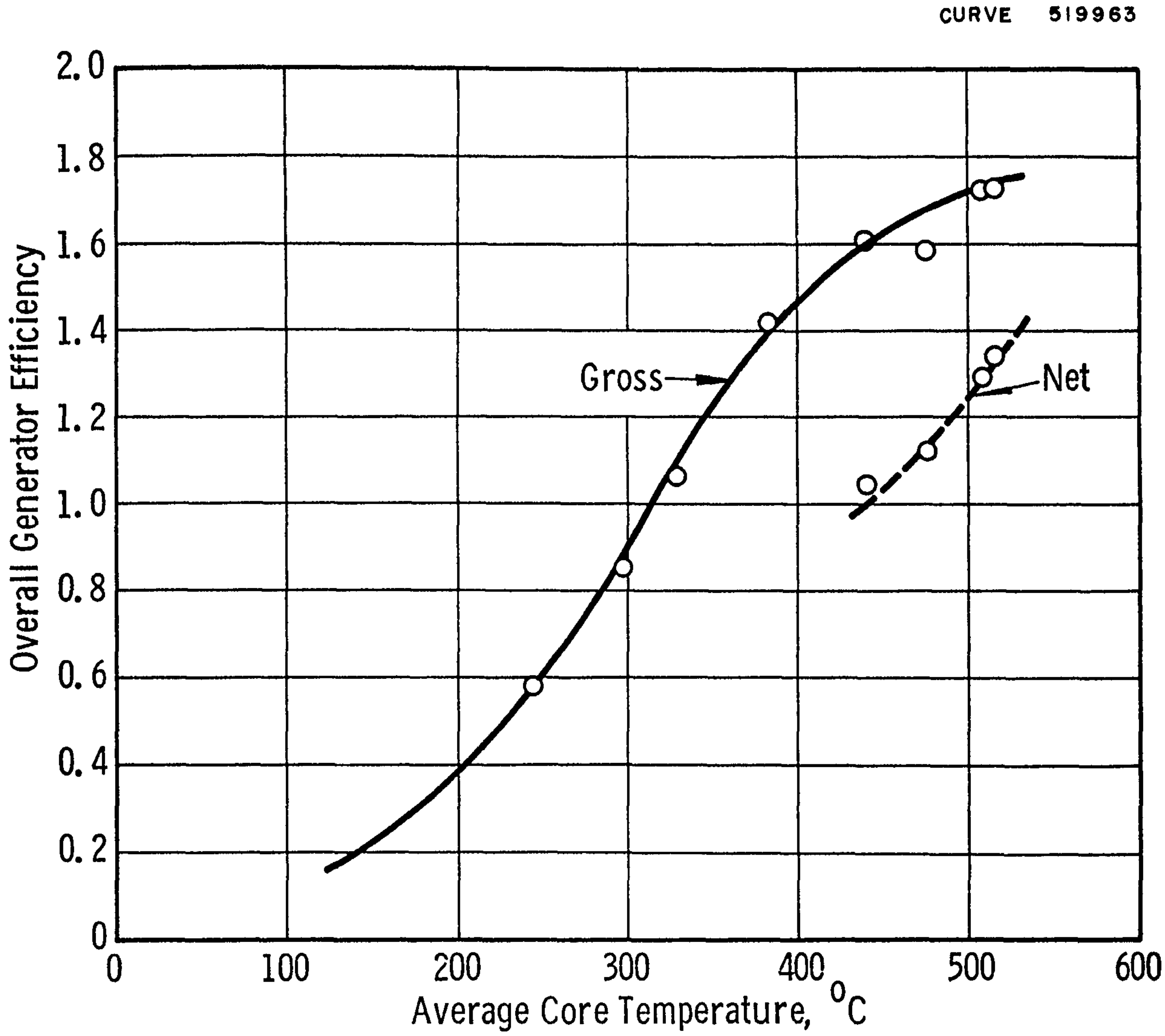


Fig. 23— Generator efficiency vs. average core temperature